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Inventor(s): Gary J. Swanson
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A SYSTEM AND METHOD FO EFFICIENT ILLUMINATION IN COLOR
PROJECTION DISPLAYS

RELATED APPLICATIONS

- This application is a continuation application of U.S. Application No.
5 08/443,180 filed on May 17, 1995 which is a continuation-in-part application of U.S.
Application No. 08/330,339 filed October 27, 1994 (abandoned) of the entire teachings
of which are incorporated herein by reference.

ABSTRACT

An illumination system for a color projection display. In one
embodiment a broad spectrum light source illuminates a multilevel
optical phase element which disperses the broad spectrum light from
the light source by diffraction. A display having a number of pixel
elements, each capable of transmitting a predetermined spectral
region, is positioned within the near field region of the multilevel
optical phase element so as to receive the light dispersed by the
multilevel phase element.

1 This invention was made with government support under contract
2 number F19628-85-C-0002 awarded by the Air Force. The government has
3 certain rights in the invention.

4 RELATED APPLICATIONS

5 This application is a continuation-in-part application of U.S.
6 Patent Application Serial No. 08/330,339, filed October 27, 1994.

7 FIELD OF THE INVENTION

8 The invention relates to illumination systems for video displays
9 and more specifically to illumination systems for color projection
10 video displays.

11 BACKGROUND OF THE INVENTION

12 Currently used techniques for color projection displays tend to
13 be relatively inefficient in their light utilization. Such low
14 efficiency limits the brightness of the display, which in effect
15 limits the acceptable amount of ambient lighting in a viewing
16 environment.

17 In certain presently used designs, light from a spectrally broad
18 source is collected by a condensing lens and illuminates a spatial
19 light modulator system. The spatial light modulator system comprises
20 a two-dimensional array of pixels and the amount of light transmitted
21 through each pixel is controlled electronically. A projection lens
22 then images the array of pixels on a viewing screen, the magnification
23 of the displayed image being determined by the particular
24 characteristics of the projection lens. The light impinging on each

1 pixel of the spatial light modulator is spectrally broad (i.e. white
2 light). Therefore, unless the system is modified to distinguish
3 colors, the display will be capable of only displaying black and white
4 images.

5 In many current systems used to modify such a system so that it
6 is capable of displaying color images each pixel of the spatial light
7 modulator is divided into three sub-pixels having equal areas. Each
8 of the three sub-pixels is covered with a micro-color filter having
9 a different spectral transmittance. For example, the filters are
10 chosen such that one filter transmits only red light, another filter
11 only green light, and the third filter only blue light. The
12 transmittances of the three sub-pixels of each pixel of the spatial
13 light modulator can be controlled independently, resulting in the
14 ability to display a color image.

15 The inefficiency of the approach can be seen by considering the
16 following factors. The light illuminating a full pixel essentially
17 is white light and, consequently, the light impinging each sub-pixel
18 is also white light. The red filtered sub-pixel will transmit only
19 red light, absorbing all of the incident green and blue light.
20 Likewise, the other two sub-pixels will transmit only its
21 corresponding color, absorbing the other two colors. It is apparent
22 that this approach utilizes, at most, only one third of the available
23 light impinging on the modulator, and absorbs the rest.

24 Furthermore, state-of-the-art microcolor filters required to
25 produce acceptable color images are only approximately only 33%
26 efficient in transmitting the color that they are designed to

1 transmit. Therefore the overall light utilization of current color
2 projection displays is about 10%.

3 One approach for improving the efficiency of color projection
4 displays is found in U.S. Patent No. 5,161,042 issued on November 3,
5 1994 to H. Hamoda. In accordance therewith, the spectrally broad
6 input light is supplied to three dichroic mirrors which reflect three
7 different color components, e.g., red, green, and blue, in different
8 directions, i.e., at different angles with respect to each other. The
9 reflected components are then supplied to an array of lenses for
10 focusing the different color components so as to converge light beams
11 of similar wavelength ranges for transmission through a liquid crystal
12 display element so as to form combined color images on a display
13 screen. A further U.S. Patent No. 5,264,880, issued on
14 November 23, 1993, to R.A. Sprague et al., discloses a similar
15 approach to that of Hamoda wherein the dichroic mirrors are replaced
16 by a blaze grating for dispersing the color components of light
17 received thereat into a spectrum of different colors at different
18 angles relative to each other.

19 It is believed that, while such approaches can be used, the
20 losses of energy of each color component are sufficient to reduce the
21 efficiencies of such systems and to show the need for further
22 improvement in such display systems. Such improved display systems
23 would minimize such losses so as to provide for substantially the
24 total use of the received energy across the color spectrum in the
25 imaging display process resulting in an improvement of the efficiency
26 of the system.

SUMMARY OF THE INVENTION

The invention relates to a color projection display in which received light, having a relatively broad spectrum, illuminates a multi-level optical phase grating so as to disperse each of the color components contained therein into a plurality of different diffraction orders. In one embodiment, the diffraction orders of each color component are then focussed onto a zero-order phase shift element which phase shifts only the undiffracted light (i.e., the zero diffraction order) with respect to the diffracted light (i.e., the higher level diffraction orders). The output of the zero-order phase shifter is then imaged onto a display having a plurality of pixels, each pixel having sub-pixel regions assigned to transmit different color components of light. The depths of the phase grating element and the zero-order phase shifter are suitably selected so that they are practical for manufacture and so that the area of chromaticity space for the color components at the image plane is maximized.

The use of such a combination of multi-level phase grating and a zero-order phase shifter, having suitably determined depths, provides desired color components at each pixel in which essentially little or no energy is lost. These color components are then suitably combined to provide a color image at each of the pixels of the display which is considerably brighter than that available using prior known systems.

In another embodiment a broad spectrum light source illuminates a multilevel optical phase element which disperses the broad spectrum light from the light source by diffraction. A display having a number of pixel elements, each capable of transmitting a predetermined

1 spectral region, is positioned within the near field region of the
2 multilevel optical phase element so as to receive the light dispersed
3 by the multilevel phase element. In one embodiment, the multilevel
4 phase element is periodic in two dimensions, thereby concentrating the
5 light in two dimensions.

6 In yet another embodiment, a method for displaying a color image
7 is disclosed. The method for displaying a color image includes
8 illuminating a multilevel optical phase element with a broad spectrum
9 light source. The multilevel phase element disperses light from the
10 light source by diffraction. A display having a plurality of pixel
11 elements, each transmitting a predetermined spectral region, is
12 positioned within the near field region of the multilevel optical
13 phase element to receive the dispersed light from the multilevel
14 optical phase element.

15 BRIEF DESCRIPTION OF THE DRAWINGS

16 This invention is pointed out with particularity in the appended
17 claims. The above and further advantages of this invention may be
18 better understood by referring to the following description taken in
19 conjunction with the accompanying drawing, in which:

20 Figs. 1 and 1A are block diagrams of an embodiment of a display
21 system using the technique of the invention;

22 Fig. 2 is a perspective diagram of an embodiment of the
23 multilevel optical phase element;

24 Fig. 2A is a perspective diagram of another embodiment of a
25 multilevel optical phase element of the invention;

1 Fig. 3 shows a graph of optimized phase grating depths of three
2 phase levels for a normalized pixel dimension for red, green and blue
3 color channels;

4 Fig. 4 shows the effective phase grating depths of three phase
5 levels for a normalized pixel dimension for the wavelengths of the
6 red, green and blue color components;

7 Fig. 5 shows the percent efficiencies of the spectral content for
8 the red, green and blue color components;

9 Fig. 6 shows the area of the chromaticity space covered when
10 using a particular embodiment of the invention on a standard 1976 CIE
11 chromaticity graph space;

12 Fig. 7 is a block diagram of another embodiment of a display
13 system of the invention;

14 Fig. 8 is a block diagram of yet another embodiment of a display
15 system of the invention; and

16 Figs. 9 and 9A are block diagrams of a multilevel phase element
17 and its complex conjugate, respectively.

18 DESCRIPTION OF THE PREFERRED EMBODIMENTS

19 In order to increase the light utilization of color displays, the
20 novel technique of the invention can be considered, in a conceptual
21 sense, as effectively concentrating all of the light of each color
22 component in a spectrally broad received light on to appropriate sub-
23 pixel regions at a color image plane, e.g., all of the incident red
24 light is concentrated in a manner such that it only illuminates the
25 sub-pixel regions corresponding to the red component thereof, all of
26 the incident green light is concentrated in a manner such that it only

1 illuminates the sub-pixel regions corresponding to the green component
2 thereof, and all of the incident blue light is concentrated in a
3 manner such that it only illuminates the sub-pixel regions
4 corresponding to the blue component thereof. By so doing, the use of
5 micro-filters is not necessary, and the theoretical light utilization
6 efficiency of such technique approaches 100%.

7 The invention achieves such light utilization based on a
8 technique referred to as aperture filling. Aperture filling is
9 described, for example, in the article, "Aperture filling of phase-
10 locked laser arrays" by G.J. Swanson et al., Optics Letters, Vol. 12,
11 April 1987. This article describes a method for increasing the energy
12 in the central lobe of a far-field pattern of a phase-locked laser
13 array. In accordance with the invention, the underlying physics of
14 this technique is modified and extended in a unique manner in order
15 to solve the color display problem of light utilization.

16 The basic physics behind aperture filling is herein described.
17 A binary amplitude grating (a grating having a transmittance of 1 or
18 0) with a fill factor (the ratio of the transmitting area to the total
19 area) of greater than or equal to 0.25, has, aside from a phase shift
20 of the zero order, a Fourier transform identical to that of a binary
21 phase grating having the same fill-factor as the binary amplitude
22 grating.

23 This statement implies that by placing a zero-order phase shift
24 element in the transform plane of an a focal imaging system, the light
25 from an aperture with a fill-factor of $\geq .25$, can be uniformly spread
26 out of fill the entire aperture. Further, by invoking reciprocity,

light from a uniform aperture can be concentrated to produce an underfilled aperture with a fill-factor of $\geq .25$.

In making use of such concepts for improving the color projection display efficiency, the above phenomenon can be modified to substantially improve the light throughput thereof. A system embodying the technique in accordance with the invention is shown in Figs. 1 and 2, wherein a multi-level, e.g., a three-level, phase grating is illuminated with a spectrally broad light from a source 10, such as a tungsten halogen bulb or a xenon arc lamp. Alternatively, the light source may comprise three separate color component sources. For example, three light emitting diodes (LEDs) or three laser sources, each emitting a separate color such as red, green, and blue color components. For the purposes of the particular description of a preferred embodiment of the invention, it is assumed that the illuminating source 10, whether a single broad spectrum source or separate color sources, primarily includes color components of the three wavelength regions, e.g., red, green, and blue. The lateral dimension of each phase level, in one embodiment, is assumed to be equal to the lateral dimension of a sub-pixel region of the spatial light modulator. For illustrative purposes only, Fig. 1A shows only two greatly magnified grating periods, each having corresponding three phase depth levels, occupying the entire aperture. It should be understood that a large plurality of grating periods, each corresponding to a pixel of the overall color image, would normally occupy an aperture.

1 If it is assumed that a first phase depth level measured with
2 respect to a second phase depth level at each grating period of the
3 phase grating 11 is equal to an integral number of wavelengths of red
4 light plus one-third of such wavelength, i.e., $(m+0.33)$ where m is an
5 integer, and the third phase depth level, again measured with respect
6 to the second phase depth level, is an integer multiple of the
7 wavelength of red light, the red light that is illuminating a three-
8 level phase grating will in effect encounter a binary phase grating
9 with a fill-factor of 33%, and a phase depth of 0.33 wavelengths. The
10 red light will be dispersed from the phase grating 11 into a zero
11 diffraction order and a plurality higher level positive and negative
12 diffraction orders which are focussed on a zero-order phase shifter
13 via lens 12. If the zero diffraction order (undiffracted) is then
14 phase shifted by about 0.33 wavelengths of red light by phase shifter
15 13, the red light exiting the system will be concentrated via a lens
16 14 so as to fill only 33% of the output imaging plane 15 (Fig. 1A).

17 The same methodology as applied above to the red light range can
18 also be applied to the green and blue light ranges. The second phase
19 depth level at each grating period equals zero wavelengths of green
20 light by definition, and the first and third phase depth levels equal
21 $(n - 0.33)$ and $n' - 0.33$ wavelengths of green light, respectively,
22 where n and n' are integers. The green light illuminating the phase
23 grating 11 will also effectively encounter a binary phase grating with
24 a fill-factor of 33%, and a phase depth of 0.33 wavelengths. If the
25 zero diffraction order is also effectively shifted by about 0.33
26 wavelengths, the green light exiting the system will be concentrated

1 so as to fill the 33% of the output imaging plane that is adjacent to
2 the 33% of the output plane occupied by the red light (Fig. 1A).

3 For the blue light, the phase depth of level of each grating
4 period, again measured with respect to the second phase depth level,
5 equals $(p' + .33)$ wavelengths of blue (where p' is an integer), and the
6 first phase depth level is an integer multiple of wavelengths of blue
7 light. The blue light illuminating the grating will also in effect
8 encounter a binary phase grating with a fill-factor of 33%, and a
9 phase depth of 0.33 wavelengths of blue light. If the zero
10 diffraction order is also effectively shifted by about 0.33
11 wavelengths, the blue light exiting the system will be concentrated
12 so as to fill the remaining 33% of the imaging plane not occupied by
13 the red light and the green light (Fig 2.).

14 The above conditions for three discrete wavelengths can in theory
15 be met to any level of accuracy. However, in practice, the accuracy
16 is limited by the physical depths of the grating levels that can be
17 practically manufactured. Furthermore, the system can be designed to
18 operate over the entire visible spectrum, rather than at only three
19 discrete wavelength regions.

20 The area of chromaticity space spanned by a particular embodiment
21 of the invention depends on the relative depths of the three phase
22 level regions of each grating period corresponding to each pixel, and
23 the depth of the zero-order phase shifter. Since the phase depths are
24 relative, and measured with respect to the second phase depth level,
25 the second phase depth level is zero by definition, thereby leaving
26 three variables: the depths of phase levels 1 and 3 with respect to
27 phase level 2, and the depth of the zero order phase shifter. These

three parameters in effect define the performance of the overall system, with the measure of performance being defined as the area of chromaticity space that is so covered. The three depth parameters are most easily optimized by performing a "global search" process that spans the range of practicable manufacturable depths. The goal thereof is to select relative depths which will maximize the area and the location of the spanned chromaticity space. An approach to such process is discussed below.

In considering the first phase level of the grating period, the phase shifts (in waves) ϕ_R^1 , ϕ_G^1 , and ϕ_B^1 of the red, green, and blue light can be expressed as:

$$\Phi_R^1 = \frac{d_1}{\lambda_R} (\eta - 1)$$

$$\Phi_G^1 = \frac{d_1}{\lambda_G} (\eta - 1)$$

$$\Phi_B^1 = \frac{d_1}{\lambda_B} (\eta - 1)$$

where η is the index of refraction of the phase grating, and d_1 is the depth of the first phase level with respect to the second phase level. As mentioned above, it is desired that the phase shift $\phi_R^1 = m + 0.33$, while the phase shift $\phi_G^1 = n - 0.33$, and the $\phi_B^1 = p$, where m , n , and p are all integers.

1 In a similar manner at the third phase level, having a depth of
2 d_3 with respect to the second phase level, the phase shifts are:

$$\Phi_R^3 = \frac{d_3}{\lambda_R} (\eta - 1)$$

$$\Phi_G^3 = \frac{d_3}{\lambda_G} (\eta - 1)$$

$$\Phi_B^3 = \frac{d_3}{\lambda_B} (\eta - 1)$$

3 Here, it is desired that the phase shift $\phi_R^3 = m'$, the phase shift ϕ_G^3
4 $= n' - 0.33$, and the phase shift $\phi_B^3 = p' + 0.33$ where m' , n' , and p' are
5 all integers.

6 Since the first and third phase levels of the grating are
7 referenced in depth to the second phase level of the grating, by
8 definition, $d_2 = 0$, and at the second phase level the phase shifts at
9 all three wavelengths is zero:

$$\Phi_R^2 = 0$$

$$\Phi_G^2 = 0$$

$$\Phi_B^2 = 0$$

1 In addition, at the zero-order phase shifter having a depth of
 2 d_4 , a phase shift of about one-third wavelength of each color is
 3 required so that at the phase shifter:

$$\Phi_R^4 = \frac{d_4}{\lambda_R} (\eta - 1)$$

$$\Phi_G^4 = \frac{d_4}{\lambda_G} (\eta - 1)$$

$$\Phi_B^4 = \frac{d_4}{\lambda_B} (\eta - 1)$$

4 where $\phi_R^4 = r + 0.33$, $\phi_G^4 = s + 0.33$ and $\phi_B^4 = t + 0.33$ (where r , s , and t are
 5 integers).

6 Since the depths of d_1 , d_2 , d_3 , and d_4 must be within practical
 7 manufacturable limits, the following practical limitations can be
 8 imposed thereon:

$$-5 \mu\text{m} \leq d_1 \leq +5 \mu\text{m}$$

$$-5 \mu\text{m} \leq d_3 \leq +5 \mu\text{m}$$

$$-5 \mu\text{m} \leq d_4 \leq +5 \mu\text{m}$$

12 and the value of η can be assumed at a conventional value, for
 13 example, of 1.5.

14 Using the above equations, those in the art can then utilize a
 15 well known global search algorithm technique, in which the values of
 16 the depths d_1 , d_3 , and d_4 are changed in steps, Δd , of approximately

0.01 μm , and used to determine in each case the area of the chromaticity space that can be spanned for each set of parameters. The depths d_1 , d_3 , and d_4 for the solution providing a maximized area can then be used as the practical physical depths for the three phase level regions at each phase grating period and the practical physical depth of the zero-order phase shifter 13.

In accordance with a specific embodiment of the invention, such a process was used to determine the three optimum depth parameters for a system operating with a uniform spectral source covering a 0.40-0.68 μm wavelength region, using both multilevel phase grating and zero-order phase shift substrates assumed to have an index of refraction of 1.5. Exemplary results for optimized sub-pixel phase grating depths of an exemplary pixel having a normalized pixel dimension are shown in Fig. 3, with the red channel having a phase grating depth 16 of 1.84 μm relative to the green channel, and the blue channel having a phase grating depth 17 of 4.0 μm relative to the green channel.

In order to illustrate how such an optimized phase grating design conforms to the theory described above, the following three discrete wavelengths can be considered: red=0.66 μm , green=0.54 μm , and blue=0.46 μm . The effective phase grating depths (modulo one-wave) of the three sub-pixels at these three phase level regions are shown in Fig. 4, where the solid line 18 represents red, the dashed line 19 represents green, and the dot-dash line 20 represents blue. It should be noted that in the first sub-pixel region, the phase grating depth for red is approximates one-third wavelength of red light, and the phase grating depths for green and blue are essentially zero. Similarly, in the second sub-pixel region, the effective phase grating

1 depth for the green approximates one-third wavelength of green light,
2 and the phase grating depths for red and blue are approximately zero.
3 In the third sub-pixel region, the effective phase grating depth for
4 blue approximates one-third wavelength of blue light, while the phase
5 grating depths for red and green are approximately zero.

6 The optimized depth for the zero-order phase shifter 13 is 0.36
7 μm , which depth corresponds to 0.27 wavelengths of red, 0.33
8 wavelengths of green, and 0.39 wavelengths of blue. For this example,
9 it is noted that the optimum phase depth is less than one wave for all
10 three wavelengths. Fig. 2 is a perspective view of a multilevel phase
11 element which repeats periodically in the x-direction. Fig. 2A is a
12 perspective view of a multilevel phase element which repeats
13 periodically in both the x and y directions. Such a configuration
14 permits the incident light to be compressed both in the x-direction,
15 as in the prior embodiment, and also in the y-direction. Methods for
16 forming such multilevel phase elements are well known to those skilled
17 in the art. In particular a method for forming such multilevel
18 diffractive optical elements is disclosed in U.S. Patent 4,895,790 to
19 Swanson and Veldkamp, assigned to the common assignee of the present
20 invention and incorporated herein by reference.

21 The system's ability to concentrate the visible spectrum into
22 three color channels is illustrated in Fig. 5 for the above-mentioned
23 0.4-0.68 μm wavelength region. The solid curve 21 represents the %
24 efficiency of the spectral content of the red channel, the dashed
25 curve 22 represents the % efficiency of the spectral content of the
26 green channel, and the dash-dot curve 23 represents the % efficiency
27 of the spectral content of the blue channel. It should be noted that

1 the red channel efficiency peaks at the wavelength of $0.66 \mu\text{m}$, the
2 green channel efficiency peaks at $0.54 \mu\text{m}$, and the blue channel
3 efficiency peaks at $0.46 \mu\text{m}$. The red channel has a secondary peak in
4 the far blue region of the spectrum. This blue light, in effect
5 "leaking" into the red channel, tends to limit the area covered in
6 chromaticity space. In some cases, it may be desired or required to
7 remove this unwanted blue light from the red channel by conventionally
8 filtering the red channel and such removal can be achieved with a
9 blue-blocking micro-filter, albeit at the cost of losing a minimal
10 amount of the blue light energy.

11 As is well known to the art, the spectral content of these three
12 color channels can then be used to determine the area of chromaticity
13 space spanned by the system. Fig. 6 shows a standard 1976 CIE
14 chromaticity space graph 25 which is well known to the art. The area
15 of the chromaticity space spanned by the embodiment discussed above
16 is depicted by three vertices of a triangle, defined by the plus
17 signs, in the graph. This area will be covered using essentially 100%
18 of the received source illumination.

19 Another embodiment of the invention does not require either the
20 zero-order phase plate 13 or the auxiliary optics 12, 14 of the
21 previous embodiment shown in Fig. 1. In this embodiment a broad
22 spectrum light source illuminates a multilevel optical phase element
23 which disperses the broad spectrum light from the light source into
24 diffraction orders. A modulation display, having a number of pixel
25 elements, each capable of transmitting a predetermined spectral
26 region, is positioned within the near field region of the multilevel
27 optical phase element so as to receive the light dispersed by the

1 multilevel phase element. In this embodiment, the free-space
 2 propagation of light from the multilevel phase element produces a 1/3
 3 wavelength phase shift of the undiffracted light with respect to the
 4 diffracted light. Because of this, the phase plate 13 and auxiliary
 5 optical elements 12, 14, which were required to produce the same zero-
 6 order phase shift in the previous embodiment, are not required in this
 7 embodiment.

8 To understand how free-space propagation provides the required
 9 1/3 wavelength zero-order phase shift, assume that the amplitude
 10 transmittance of the phase grating is expressed as:

$$t(x) = a_0 + \sum_n a_n \exp \left[i 2 \pi \frac{n}{T} x \right]$$

11 where T is the grating period, a_0 is the amplitude of the
 12 undiffracted light, the a_n 's are the amplitude coefficients of the
 13 various diffracted orders, and n is an indexing parameter.

14 If a unit amplitude plane wave illuminates this phase grating,
 15 the light amplitude distribution, U_z , at a distance Z from the grating
 16 plane is described by:

$$U_z(x) = a_0 + \sum_n a_n \exp \left[i 2 \pi \frac{n}{T} x \right] \exp \left[-i \pi \lambda \frac{n^2}{T^2} Z \right].$$

17 where λ is the wavelength of the unit amplitude plane wave. The
 18 irrelevant constants have been omitted from this equation. Thus the
 19 free-space propagation over the distance Z has the effect of
 20 introducing phase shifts to the diffracted components with respect to
 21 the undiffracted component.

1 A distance, $Z_{1/3}$, is defined by the equation:

$$Z_{1/3} = \frac{2T^2}{3\lambda}$$

2 where λ is the central wavelength of the spectral distribution.

3 Substituting this equation for $Z_{1/3}$ into X in the previous
4 equation, results in the following light distribution:

$$U_{z_{1/3}}(x) = a_0 + \sum_n a_n \exp[i2\pi \frac{n}{T}x] \exp[-i\frac{2}{3}\pi n^2]$$

5 The resulting phase shift (for all values of n that do not result
6 in an integer when divided by 3) is equal to an integer number of
7 wavelengths plus 1/3 wavelength. Since the integer number of waves
8 of phase shift are irrelevant, all of the values of n (that do not
9 result in an integer when divided by 3) effectively see a 1/3 wave
10 phase shift with respect to the undiffracted light. For values of n
11 that do result in an integer when divided by 3, the result is an
12 integer number of wavelengths of phase shift. However, for the
13 grating described above, the a_n 's (for n divisible by 3) are zero.

14 Thus, the net result of free-space propagation over the distance
15 $Z_{1/3}$, is to produce a light distribution where the undiffracted light
16 is phase-shifted by 1/3 wavelength with respect to the diffracted
17 light. It is at this location that the modulation display, such as
18 a liquid crystal light modulator, is placed. With such a positioning,
19 no phase shift element 13 or additional optics 12, 14 are needed.

It should be noted that the propagation distance $Z_{1/3}$ is a function of wavelength. Therefore, the free-space propagation just discussed is strictly accurate at only one wavelength. However, acceptable performance over the whole visible spectrum may be achieved by choosing the $Z_{1/3}$ distance to correspond to the wavelength at the center of the spectrum. That is, $Z_{1/3}$ should be chosen such that

$$\frac{2T^2}{3\lambda_{long}} < Z_{1/3} < \frac{2T^2}{3\lambda_{short}}$$

where λ_{long} is the longest wavelength of interest and λ_{short} is the shortest wavelength of interest.

The above analysis assumes that the illumination source is a point source at infinity, resulting in plane wave illumination. If the illumination source is such that the approximation of a point source at infinity which was just discussed is not valid, an embodiment which describes a physically extended illumination source must be considered.

In this embodiment, shown in Fig. 7, an illumination source 10' has a dimension (for purposes of discussion referred to as the x-dimension) of S_c . A condensing lens 30 having a focal length of F_c , is positioned adjacent the illumination source 10', at a distance of F_c . This configuration results in an angular source extent in the x-dimension of $\theta_c \approx S_c/F_c$.

A figure of merit for performance is the ratio b/T , where b , the blur, is the physical extent of the light pattern at the display location in the x-dimension and T is the grating period. For good

1 performance, this ratio is less (typically much less) than 1/3. If
 2 b is given by the expression $b = Z_{1/3}\theta_c$, the figure of merit becomes:

$$\frac{b}{T} = \frac{2T}{3\lambda_o}\theta_c$$

3 where λ_o is the center wavelength. For example, if an acceptable
 4 figure of merit is 1/6, the center wavelength is .55 micrometers, and
 5 the grating period is 48 micrometers, the resulting value for the
 6 angular source size is $\theta_o = 2.9$ milliradians. Thus, for a 50 mm focal
 7 length condensing lens, a source with a size no larger than 145
 8 micrometers in the x-dimension is required for this figure of merit
 9 to hold. Hence, a source 10' with a physical dimension smaller than
 10 most commercially available broad-spectrum incoherent sources should
 11 be used to obtain good performance. Although broad spectrum
 12 incoherent sources of the dimension just described are not generally
 13 available, three spatially coherent monochromatic sources, such as 3
 14 different wavelength LED's or laser diodes, could readily be used as
 15 the illumination source 10'. As discussed with respect to the
 16 previous example, the modulation display should be placed at a
 17 distance $Z_{1/3}$ from the multilevel phase element 11.

18 Referring to Fig. 8, an embodiment which increases the extended
 19 source performance includes a lenslet array 40 (in one embodiment
 20 cylindrical lenslets), placed between the condensing lens 30 and the
 21 multilevel phase element 11. The focal length of each lenslet 42 is
 22 F_m , and the distance between the lenslet array 40 and the multilevel
 23 phase element 11 is $Z_s + F_m$. Thus, Z_s is the distance between the
 24 imaged source 22 and the multilevel phase element 11. Each lenslet 42

1 focusses an image 44 of the extended source, S_c , at a distance F_m from
 2 the lenslet array 40. Each of these imaged sources 44 will be of
 3 physical dimension, S_m , in the x-dimension, where $S_m = (F_m S_c)/F_c$
 4 centered about the optical axis of the respective lenslet 42.

5 For an image 44 of dimension S_m that lies on the optical axis of
 6 the condensing lens, a Fresnel diffraction calculation indicates that
 7 the light amplitude distribution at a distance Z from the multilevel
 8 phase element 11 is given by the expression:

$$U'_{z(x)} = \exp\left[i\frac{\pi}{\lambda} \frac{x^2}{Z+Z_s}\right] \left[a_o + \sum_n \exp\left[-i\pi\lambda \frac{n^2}{T^2} \frac{Z_s Z}{Z+Z_s}\right] \exp\left[-i2\pi \frac{n}{T} \frac{Z_s}{Z+Z_s} x\right]\right]$$

9 in which the irrelevant constant factors have been neglected.
 10 The first exponential term in the series is the wavefront curvature
 11 introduced by the lenslet 44. The first exponential term after the
 12 summation sign represents the phase shifts incurred by the various
 13 diffraction orders. Again, what is desired is for all of the phase
 14 shifts for values of n which do not result in integers, when divided
 15 by three, be equal to $1/3$ wave. For this to be the case, Z must be
 16 given by the expression:

$$Z = \frac{2T^2 Z_s}{3\lambda Z_s - 2T^2}$$

17 Hence, in a manner similar to the case without lenslets, the
 18 value of Z should be chosen such that:

$$\frac{2T^2Z_s}{3\lambda_{long}Z_s-2T^2} < Z < \frac{2T^2Z_s}{3\lambda_{short}Z_s-2T^2}$$

wherein T is the periodicity of said multilevel optical phase element, Z_s is equal to the distance between said multilevel optical phase element and said lenslets minus the focal length of said lenslets, λ_{long} is the longest wavelength of interest and λ_{short} is the shortest wavelength of interest.

Comparing this relationship with the relationship previously shown for $Z_{1/3}$ (the optimum distance for the plane wave illumination case):

$$\frac{Z_{1/3}}{Z} = 1 - \frac{2T^2}{3\lambda Z_s}$$

As Z_s approaches infinity, the distance, Z, approaches $Z_{1/3}$, as is expected. For finite source distance Z_s , the optimum Z distance is greater than the plane wave distance $Z_{1/3}$.

The last exponential term indicates that the period of the light distribution at the optimum Z distance is no longer equal to the period of the original phase grating. In effect, free-space propagation from a source 10' located a finite distance from the grating 11 results in a magnification. This magnification, M, is given by the equation:

$$\frac{1}{M} = 1 - \frac{Z}{Z_s}$$

1 Note that for a finite source distance, Z_s , the magnification factor
2 is greater than one.

3 The angular source size of the extended source 10 as seen at the
4 grating 11, S_m/Z_s . This angular source size results in a new blur
5 dimension, b_n , given by the expression:

$$b_n = \frac{S_m}{Z_s} Z = \frac{2T^2}{3\lambda Z_s - 2T^2} S_m$$

6 Because of the magnification described above, the new period of
7 the image pattern is, T_n :

$$T_n = MT = \frac{3\lambda Z_s T}{3\lambda Z_s - 2T^2}$$

8 The resulting fractional blur of the image pattern can now be
9 described by the relationships:

$$\frac{b_n}{T_n} = \frac{2T}{3\lambda Z_s} S_m = \frac{2T}{3\lambda Z_s} \frac{F_m}{F_c} S_c$$

10 The fractional blur, with the lenslet array 40 in position, can
11 be directly related to the fractional blur, b/T , without the lenslet
12 array 40, according to the expression:

$$\frac{b_n}{T_n} = \frac{b}{T} \frac{F_m}{Z_s}$$

1 This relationship clearly shows that the blurring can be dramatically
2 reduced by the proper introduction of the lenslet array 40. The
3 reduction factor of the blurring is the ratio F_m/Z_s .

4 So far, consideration has only been given to the one lenslet 43
5 centered on the optical axis (OA) of the condensing lens 30.
6 Additional lenslets placed adjacent to the original lenslet 43 behave
7 in a manner identical to that described above for the original lenslet
8 43. However, because of a coherent interaction between the light
9 traversing different lenslets, an additional constraint is placed on
10 the allowable center-to-center spacings of the lenslets. The minimum
11 center-to-center spacing distance of the lenslets, L , is given by the
12 expression:

$$L = pT \left(\frac{Z + Z_s}{Z} \right)$$

13 where p is a positive integer.

14 In another embodiment, the multilevel phase element 11' shown in
15 Fig. 9, and discussed above with respect to Fig. 3, includes a double
16 step having an aggregate height of $4.0 \mu\text{m}$. The first step is $1.84 \mu\text{m}$
17 measured from the base of the phase element and the second step is
18 $2.16 \mu\text{m}$ measured from the top of the first step to the top of the
19 phase element. A phase element constructed with these dimensions will
20 function as described above.

21 If instead of the phase element 11' shown, a complex conjugate
22 phase element 11'' as shown in Fig. 9A is constructed, the complex
23 conjugate phase element 11'' will perform equivalently to the phase
24 element 11'. The reason for referring to phase element 11'' as a

complex conjugate phase element will become readily apparent if the complex conjugate phase element 11'' is placed adjacent the phase element 11' such that the steps are aligned. Light passing through both phase elements will be unaffected, and thus, just as the integration of a wavefunction by its complex conjugate equals one, phase element 11'' acts as the complex conjugate to phase element 11, thereby permitting the incident light to pass both elements through unaffected.

Unlike the phase element 11', the complex conjugate phase element 11'' $Z_{1/3}$ is defined by:

$$Z_{1/3} = \frac{T^2}{3\lambda}$$

wherein λ is the central wavelength of the spectral distribution.

To achieve acceptable performance over the whole visible spectrum may be achieved by choosing the $Z_{1/3}$ distance to correspond to the wavelength at the center of the spectrum.

$$\frac{T^2}{3\lambda_{long}} < Z_{1/3} < \frac{T^2}{3\lambda_{short}}$$

where λ_{long} is the longest wavelength of interest and λ_{short} is the shortest wavelength of interest. Similarly, when lenslets are employed in conjunction with the complex conjugate phase element 11'', Z must be chosen such that:

$$\frac{T^2 Z_s}{3\lambda_{\text{long}} Z_s - T^2} < Z < \frac{T^2 Z_s}{3\lambda_{\text{short}} Z_s - T^2}$$

1 wherein T is the periodicity of said multilevel optical phase
 2 element, Z_s is equal to the distance between said multilevel optical
 3 phase element and said lenslets minus the focal length of said
 4 lenslets, λ_{long} is the longest wavelength of interest and λ_{short} is the
 5 shortest wavelength of interest. Thus, using a complex conjugate
 6 phase element permits a closer spacing than is permitted by the non-
 7 complex conjugate phase element.

8 Having shown the preferred embodiment, those skilled in the art
 9 will realize many variations are possible which will still be within
 10 the scope and spirit of the claimed invention. Therefore, it is the
 11 intention to limit the invention only as indicated by the scope of the
 12 following claims.